Development of A Deep Geological Repository System for High-level Waste in Korea: R&D Activities and Status

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ABSTRACT

This study represents the basic approaches with specific activities to develop a reference deep geological repository system with reasonable rationale from the aspects of technology, economics and long-term safety. The safety philosophy in developing a reference concept is based on the multiple barrier principle, i.e. safety does not depend on the performance of a single barrier. As a step-by-step process, the overall approaches with specific activities for developing a reference repository system are : 1) a selection of reference spent fuel; 2) a determination of the basic assumptions and the technical/safety criteria for system design requirements; 3) screening the most promising option by qualitative analysis, comparison and ranking of the proposed repository alternatives with respect to the technical feasibility, the long-term safety and the cost aspects; 4) a pre-conceptual design to define a reference repository system. This paper also includes results from the relevant R&D activities that have being performed during the past three years in accordance with such development plan basic assumptions

INTRODUCTION

Korea Atomic Energy Research Institute (KAERI) has been undergoing a R&D program for HLW disposal technology development since 1997. The main purpose of this program is to establish a reference HLW repository concept by the year 2006. The disposal concept being conceived in the study is to encapsulate the spent fuel in corrosion resistant containers. The spent fuel packages are then to be deposited in a mined underground facility located at about 500m depth in crystalline rock. No site has been specified but a generic site with granitic rock is considered for the study. Then, the waste packages are placed in boreholes that are drilled along with the centreline of the floors in a system of parallel deposition tunnels. For the development of a reference HLW repository concept, different alternatives concerning the emplacement patterns of the container were suggested as well as different distances between deposition holes and tunnels. Through some qualitative comparison and analysis of such alternatives, a preliminary basic concept was screened out and it is being developed into a repository system at pre-conceptual level.

This paper represents the directions and the basic approaches, with essential specific activities, needed to determine the most promising option through the system alternative study and then, to develop a reference deep geological repository system with technical feasibility, reasonable cost and long-term safety. The safety philosophy in developing a reference concept is based on the multiple barrier principle, i.e. safety does not depend on the performance of a single barrier. The approaching steps for the reference concept development of a Korean geological repository system are as follows (see Fig.1) :

1 Selection of the reference spent fuel as one of the design bases.
2 Determination of the basic assumptions/ground rules and the technical/safety criteria for system design requirements.
3 Alternative system study regarding spent fuel packages, near field design, repository layout and performance assessment: qualitative analysis, comparison and ranking of feasible alternatives with respect to the technical feasibility, the long-term safety and the cost aspects.
4 Pre-conceptual design of repository system including surface and underground facilities and Sensitivity analyses to define a reference repository concept with respect to spent fuel burnup and age, disposal capacity, disposal depth, retrieval operation option (with or without buffer/backfill, backfilling time, etc.) and usage of multi-purpose

(storage, transportation and disposal) container or cask.

With regards to thus step-by-step approach, it begins with many alternatives and it screens out alternatives progressively. It is initially based on brief analyses, and later based on more and more detailed studies.

STEP 1&2 : DETERMINATION OF THE REFERENCE SPENT FUEL AND THE BASIC ASSUMPTIONS AND GENERAL CRITERIA

The first activity in the scheme, as shown in Fig.1, is to define the reference spent fuel to be disposed of, what type it is, in what form it is, the radionuclide inventory, the residual heat, etc. In the screening processes to define a reference spent fuel, it should be considered that a broad variation of characteristics of spent fuel must be accommodated by any future repository. As the radiological and heat sources, the spent fuel, waste itself, influences the basis of repository design (e.g. container, layout and configuration of containers in underground, deposition tunnel/borehole size, etc.). Therefore, the reference spent fuel has to be determined to be a representative of the average spent fuel to be disposed of.

The second activity is to determine the ground rules and basic assumptions and to determine the functional and technical criteria needed to be applied in developing and defining the reference repository concept. This mainly comprises the assumed disposal capacity and depth, the properties of geologic medium as repository host rock, the radiological safety criteria for repository operation and post-closure phase, etc. This information, however, is not necessarily fixed, but may be changed in parts during the course of the repository study due to new scientific information or adjustments of waste management policies or strategies. In order to revise and improve them, more specific information should be collected by the site characterization processes and the repository system design and performance assessments. It is also important to investigate closely the other countries' repository concepts and safety/technical criteria that would be developed further.

The followings are some parts of the results from the R&D activities that have been completed during the past three years.

Reference Spent Fuel

The two types of reference spent fuel (PWR and CANDU fuels) were chosen by screening the representative characteristics of all spent fuels from the existing and planned nuclear power plant [1]. A proposed range in characteristics provides a greater confidence in the reliability of the results in repository behavioral predictions. The characteristic bounding data of the reference spent fuels should encompass a variation of characteristics in all existing and future spent fuels of interest. The properties of the reference fuels are summarized as :

- types of the reference spent fuel
  - spent PWR fuel assembly
    - fuel rod array : 17 x 17
    - total weight and dimensions : 665 kg, 21.4^2 cm^2 (cross-section) x 453 cm (length)
    - decay heat per assembly : 385 watt/assembly
  - spent CANDU fuel bundle
    - fuel rod array : 37 rods in bundle
    - total weight and dimensions : 25 kg, 10 cm (diameter) x 49.5 cm (length)
    - decay heat per bundle : 2.28 watt/bundle
- initial enrichment and discharge burnup of the reference fuel
  - spent PWR fuel assembly
    - nominal burnup case : 4.0wt.% for 45,000MWd/tHM
    - high burnup case : 4.5wt.% for 55,000MWd
  - spent CANDU fuel bundle
    - 0.71 wt.% (natural uranium) for 7,500 MWd/tHM
- cooling time before disposal : 40years

Disposal Capacity : 36,000 ton of heavy metal (tHM)

The total spent fuel inventories to be disposed of are estimated under the assumption that total nuclear reactors in operation by 2015 are 26 PWR reactors and 4 CANDU reactors and their lifetimes are all 40 years with the exception of 30 years for Kori-1.

- spent PWR fuel : 20,000 tHM (45,500 assemblies)
- spent CANDU fuel : 16,000 tHM (820,000 bundles)

Radiation Protection and Long-term Disposal Safety Criteria

The overall radiation protection principle and safety criteria are one of the most important parameters that must be taken into account since when planning a HLW repository system. Such basic criteria are based on the international organizations' recommendations and the design bases of several countries' disposal concepts [2-5] and on the MOST's Notice [6], that was recently published.

Fundamentally, a repository system shall not be dependent for its long-term safety on monitoring and maintenance by future generations. This does not mean, however, that the repository cannot be monitored for a period after disposal of the waste or closure of the repository.

The long-term safety of the repository should be based on passive multiple barriers so that the degradation of one barrier does not substantially impair the overall performance of the disposal system.

During the operational phase, the radiation dose to individuals caused by the planned activities in the encapsulation and emplacement processes shall be less that 20 mSv/year (2 rem/year) for the whole body. During a reasonably predictable period of time after the closure of the repository, the doses to individuals caused by expected releases should be less than 0.1 mSv/year (10 mrem/year) representing a risk of less than 10^{-5}/year.

Particularly great attention should be given to describing protection for the period up to closure of the repository and the first thousand years thereafter, with a special focus on nearby residents.

The individual dose up to about 10,000 years (that could consider the next ice age) should be quantitatively reported as a best estimate with an estimated margin of error. Environmental protection should be described for the same period of time. After the period, qualitative assessments should be made of what might happen with the repository, including deliberations regarding the risk of increased releases.

STEP 3 : DETERMINATION OF THE DESIGN BASIS DISPOSAL CONCEPT

Once the bases are outlined as mentioned in step 1&2, the system alternative study starts in order to find the most feasible option that has potentials and reasonable rationale in developing to the desirable concept. This step would be done on a broad scale and logically, in steps starting with the work to define the environmental conditions in the bedrock. Unfortunately, no site has been specified yet. The granitic rock is merely considered as a potential host rock medium of the repository at present conceptual study phase. Then one can proceed to find a reference container, which is incorporated into the design of the underground repository. This starts with a number of feasible alternatives. In comparing the pros and cons of different alternatives from the aspects of technical feasibility, cost and safety principle, a specific one (or with another alternative) is selected as the most promising option.

In the step of "*Fuel Packaging Options*", various design concepts of the container alternatives are considered and compared with regards to the aspects of the fabrication technology, the long-term integrity and the cost. Thus a top ranked alternative will be chosen for the near-field design work, i.e. the geometry of the deposition hole or geometry of the deposition tunnel in the case of in-tunnel emplacement. The design of the container and the design of the near-field may be practically non-dependent of site specific data, so that relatively detailed analysing works can be made in an early stage based on only general information of the physicochemical properties of the representative crystalline rock available elsewhere [7-9].

The following step labelled "*Repository Layout*" is to calculate how the containers can be configured in the underground repository. This step involves the thermal calculations to derive the deposition holes and/or tunnels spacing meeting with thermomechanical safety constraints for the integrity of the near-field components. The preliminary study results show that the maximum temperature in the bentonite buffer determines the distance between containers and consequently the length of tunnels to be excavated, and the thickness of the bentonite buffer. Thus, the thermal calculations based on the different thermal properties of the container, the buffer and the rock result in the cost differences between alternatives.

Once the repository layout is determined, the technical feasibility of the repository alternatives with the specific deposition tunnel/hole spacing and the container emplacement mode has to be evaluated. It would be done with regard to the constructability, the deposition and sealing technology (including the operation safety) and the possibility of human intrusion. For the analysis of the deposition/sealing technology, emplacing modes of the buffer and the container (e.g. buffer and container separately or in one package, with or without surrounding radiation shield, transportation/handling, etc.) and the sealing technology for closure are considered from a conceived practical operation point of view.

The first activity in the comparison of the long-term performance and safety of the repository concepts is to specify the design parameters for each alternative, such as geometry and spacing of deposition holes/tunnels, and type of emplacement mode. Based on this information, the initial and long-term performance of the individual barrier in each alternative, as well as, effects if interactions between barriers are qualitatively evaluated. The sensitivity of the performance of the barriers to future events, with a potential detrimental effect, is also qualitatively assessed.

In the next step, the individual barriers of each alternative are compared in order to get the relative importance of the different barriers for the safety and to identify differences in barrier performance between the alternatives. The relative importance of a barrier for the safety is a key factor to determine the importance of an identified difference between the concepts. Finally a qualitative comparison between the alternative concepts is performed based on a set of the evaluation criteria (i.e. dose limit, possibility of validation, the sensitivity to rare events, etc.). Here, the safety evaluation of the individual barriers is combined with an evaluation of overall safety. This will show the degree to which that repository safety is dependant on the performance of the total system rather than that of a single barrier.

However, it may be practically difficult to distinguish any major quantitative difference in the safety of the repository alternatives because their major design parameters and multiple barriers are similar to each other. In that case, the final evaluation for a reference concept should be controlled by differences in the results of the evaluation of the technology and cost aspects.

In accordance with the specific activities as mentioned above, one of the major subsystems consisting of the repository system conceived in this study is to encapsulate the spent fuel in a corrosion resistant container. High-Ni Alloy, stainless steel and copper are considered as the corrosion resistant material of the disposal container and carbon steel is the insert material for the container strength. Regarding the significantly different physical properties of spent PWR and CANDU fuels, two types of container concepts are sketched, as shown in Fig. 2 and 3. One is the separate-packaged concept in which 4 spent PWR fuel assemblies and 333 spent CANDU fuel bundles can be encapsulated into independent containers. The other one, co-packaged concept is to accommodate 4 spent PWR fuels and 72 CANDU fuel bundles in the common container. This concept may reduce total numbers of the disposal containers to be disposed of in the underground repository, which results in the simplification of the handling, transportation and emplacement processes in the surface and underground facilities. More detailed analyzing works have being carried out from the aspects of the mechanical/structural safety and nuclear criticality and radiation safety.

The containers, which transported from the encapsulation facility, could be placed in vertical boreholes from the floor in a disposal tunnel or in horizontal boreholes from an access tunnel. Seven different alternatives concerning such emplacement patterns of the container are developed, as listed in Table 1. In this table, the deposition hole and the tunnel spacing are given with respect to each alternative, which was estimated based on the thermal constraint of the bentonite buffer material.

The layouts of waste packages in the underground repository with respect to each alternative are sketched, and then the specific thermal loads, the required disposal area, and the excavation rates are estimated as shown in Fig.4, as an example. Based upon this information, the alternatives are narrowed down to VSA concept as the most promising option(s) by a typical pair-wise comparison method, which is being under pre-conceptual designing step.

STEP 4 : PRE-CONCEPTUAL DESIGN OF THE REPOSITORY

The pre-conceptual design activities concern some more detailed work regarding the top ranked repository concept selected in the previous step for developing a "Reference Disposal Concept". In this step, the surface facilities for spent fuel packaging and the underground repository system are designed at pre-conceptual level and then integrated into an entire repository system with the sketches of the necessary equipment and facilities. The key issues of this step are :

- design and layout of the repository system in accordance with the basic assumptions and the technical/safety criteria established in the step 1&2,
- constructability analysis, which indicates how the repository will look like "as built", and
- quantitative safety assessment of the repository system.

In the preliminary design phase, data specified for the above issues are necessarily flexible. In many cases, specific values may not be known and are therefore assumed. In other cases, new scientific information may become available or conditions may change that warrant adjusting the values of particular data. Still this step is not site specific because there is no site characterization data that ties repository performance to a specific site in Korea. As such, design parameters and performance assessment criteria are necessarily general in nature. In this step, it is important to recognize the limitations of these data and parameter sets and how this effects the preliminary design. Basically, the preliminary design aim to provide a good first estimate of the repository in terms of its functionality, cost, and safety to the public and the environment.

At present, a preliminary conceptual design is being carried out. Major design parameters and assumptions are summarized in Table 2. Fig 5 shows a schematic diagram of underground repository system to dispose spent PWR and CANDU fuels.

The more detailed design works may well result in changes to the preliminary design, but these changes will reflect a careful understanding of all the initial input with respect to any changes. Changes may be due to refinement of data or concepts, inclusion of uncertainty associated with data values, new scientific evidence, new or revised regulations, programmatic re-direction, or shifts in governmental policy.

ACKNOWLEDGEMENTS

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Table 1. Emplacement alternatives of waste packages

Item	Case	Emplacement Method	Arrangements due to thermal load	Disposal Density ($kgHM/m^2$) [3)]
Vertical Emplace-ment	**VAT**	Each separate-packaged PWR or CANDU fuel container is vertically emplaced in alternative deposition tunnels.	▪ Borehole Spacing : 6 m ▪ Tunnel Spacing : 40 m ▪ Container Surface Temp.: 93°C	9.0
	VSA	Each separate-packaged PWR or CANDU fuel container is vertically emplaced in separate deposition area.	* Refer to note 1)	9.0
	VCop	Co-packaged PWR/CANDU fuel container is vertically emplaced.	▪ Borehole Spacing : 10 m ▪ Tunnel Spacing: 40 m ▪ Container Surface Temp.: 93°C	9.0
	VAT-SPDC	For PWR fuel deposition tunnel, one container is vertically emplaced in one borehole and for CANDU fuel deposition tunnel two canisters in one hole.	▪ Borehole Spacing : 6 m ▪ Tunnel Spacing : 40 m ▪ Container Surface Temp.: 96°C	6.1
Horizon-tal Emplace-ment	**HAT**	Each separate-packaged PWR or CANDU fuel container is horizontally emplaced in alternative deposition tunnels.	▪ Borehole Spacing : 6 m ▪ Tunnel Spacing : 40 m ▪ Container Surface Temp.: 94°C	8.5
	HAS	Each separate-packaged PWR or CANDU fuel container is horizontally emplaced in separate deposition area.	* Refer to Note 2)	9.3
	HCop	Co-packaged PWR/CANDU fuel container is horizontally emplaced.	▪ Borehole Spacing : 6 m ▪ Tunnel Spacing : 40 m ▪ Container Surface Temp.: 93°C	8.8

Note :

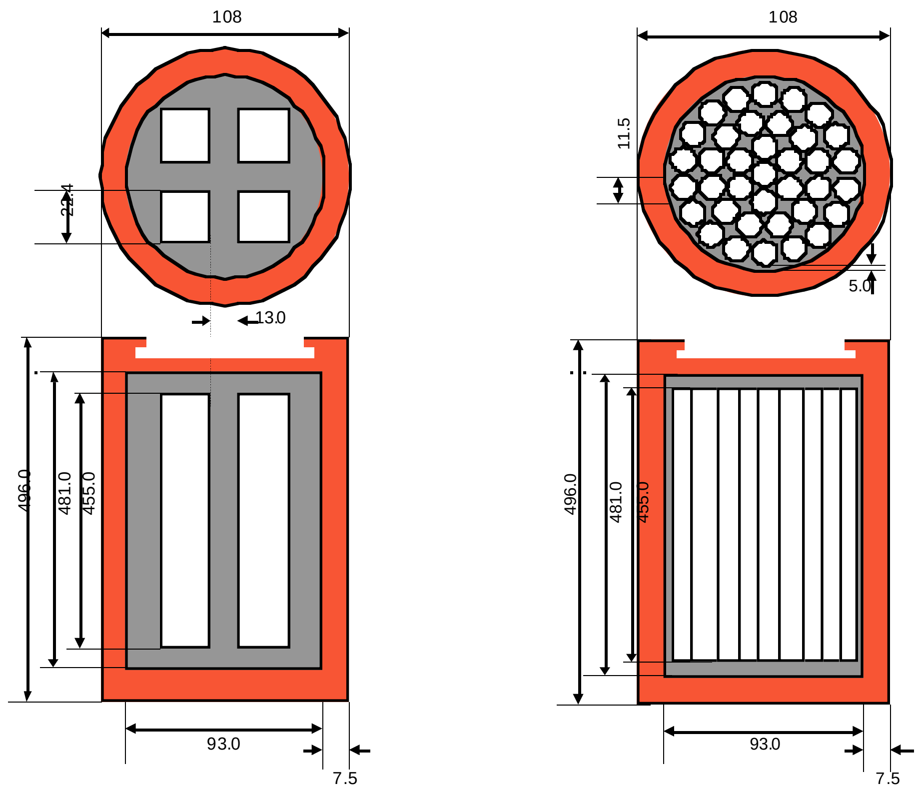
1) PWR fuel deposition area :
   Container spacing : 6 m
   Deposition tunnel spacing : 40 m
   Container surface temperature : 93ºC

   CANDU fuel deposition area :
   Container Spacing : 3 m
   Deposition tunnel spacing : 40 m
   Container surface temperature : 87°C

2) PWR fuel deposition area :
   Container spacing : 6 m
   Deposition tunnel spacing : 40 m
   Container surface temperature : 97ºC

   CANDU fuel deposition area :
   Container Spacing : 6 m
   Deposition tunnel spacing : 20 m
   Container surface temperature : 86°C

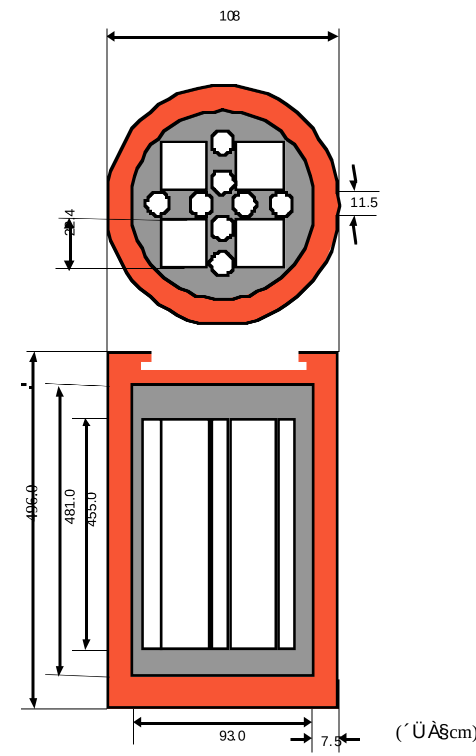
3) (total amount of spent fuel to be disposed of, kg of heavy metal)/(required area to accommodate all waste containers in accordance with the given alternatives, m^2)



- ❖ Canister Outer shell : Ni-Alloy
- ❖ Cast Insert (Fuel region) : Carbon steel
- ❖ Capacity : 4 PWR Spent Fuel Assemblies
- ❖ 11,375 containers
- ❖ Residual Heat in Canister : 1,540 Watt
- ❖ Total Volume : 4,513 m^3
- ❖ Surface : 19 m^2
- ❖ Total Weight : 31,734kg
  - ☞ Fuel wt. : 2,660 kg
  - ☞ Cast Insert : 19,189kg
  - ☞ Container wt. : 9,885 kg (Ni-alloy)

- ❖ Canister Outer shell : Ni-Alloy
- ❖ Cast Insert (Fuel region) : Carbon steel
- ❖ Capacity : 333 Bundles (37 tubes x 9 stacks)
- ❖ 2,529 canisters
- ❖ Residual Heat in Canister : 760 Watt
- ❖ Total Volume : 4,513 m^3
- ❖ Surface : 19 m^2
- ❖ Total Weight : 33,738kg
  - ☞ Fuel wt. : 8,325 kg
  - ☞ Cast Insert : 15,528kg
  - ☞ Outer-shell wt. : 9,885 kg (Ni-alloy)

Fig. 2. Schematic Diagram of the Separated-packaging Concept for the Disposal Containers for Spent PWR and CANDU Fuels



- ❖ Canister Outer shell : Ni-Alloy
- ❖ Cast Insert (Fuel region) : Carbon steel
- ❖ Capacity : 4 PWRs + 8x9 CANDUs
- ❖ 11,375 Co-packaged containers
- ❖ Residual Heat in Container : 1,704 Watt
- ❖ Total Volume : 4,513 m^3
- ❖ Surface : 19 m^2
- ❖ Total Weight : 32,889kg
  - ☞ Fuel wt. : 4,550kg
  - ☞ Cast Insert : 18,454kg
  - ☞ Outer-shell wt. : 9,885 kg (Ni-alloy)

Fig. 3. Schematic Diagram of the Co-packaging Concept for the Disposal Containers for Spent PWR and CANDU Fuels.

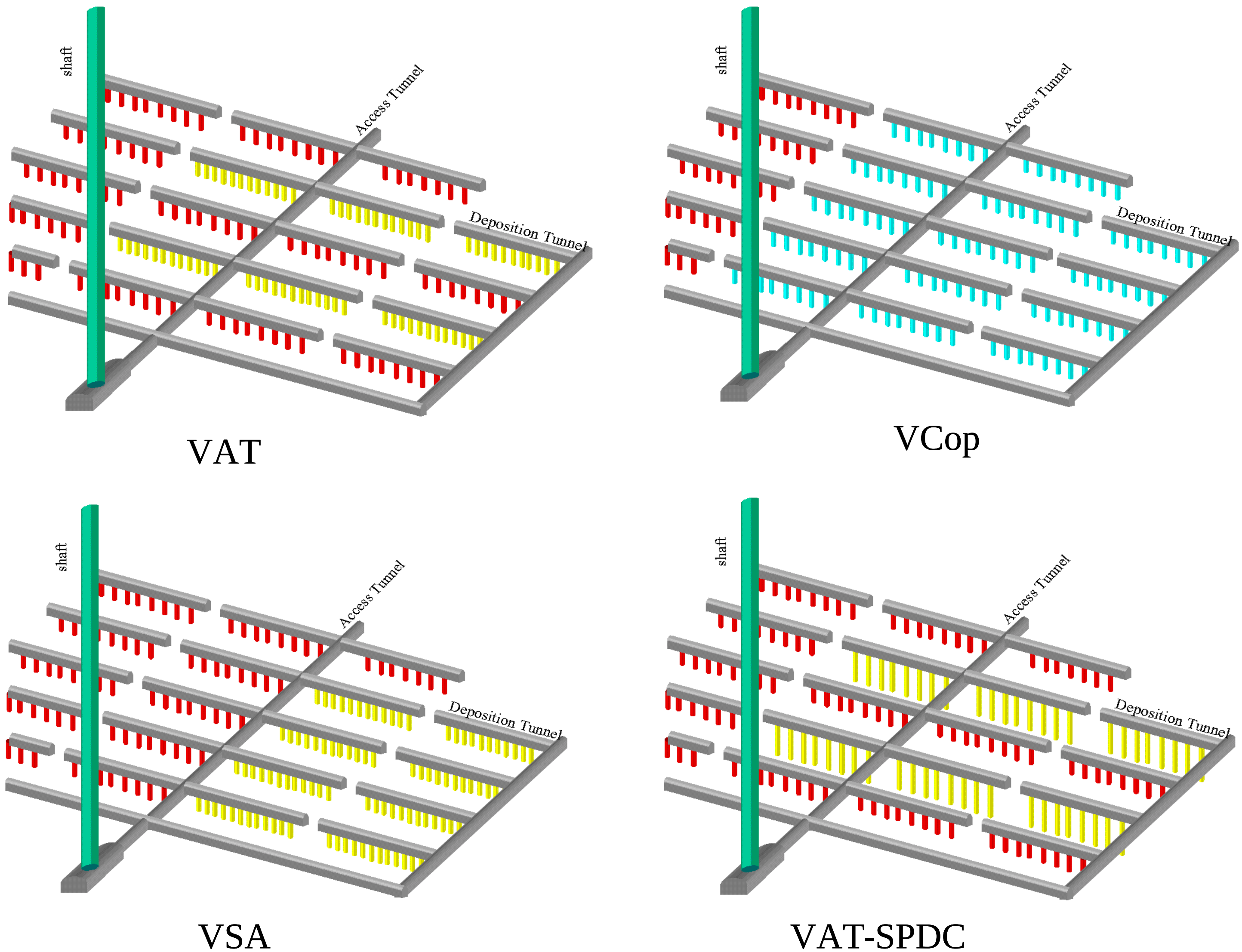


Fig. Alternatives for Vertical Emplacement

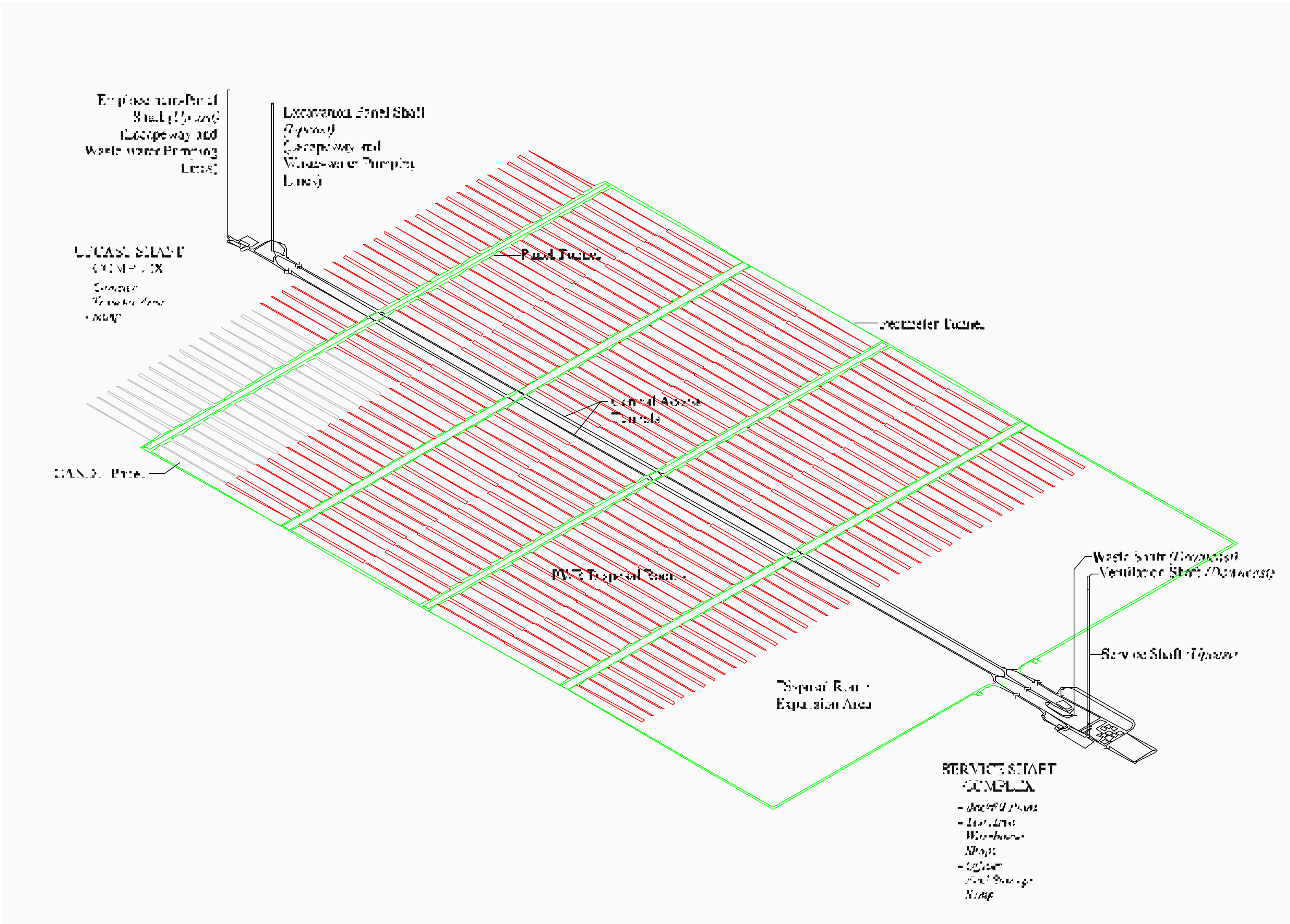


Fig. Schmati Diagram of Undergrounc Repository System

Table 2. Base Case Design Components for Conceptual Design Evaluation

Design Parameter	Assumption
Waste and Disposal Canisters	
Waste Form	PWR and CANDU
Waste Volume	36,000 MTU
Waste Throughput (receipt *rate* expandable by 20%)	CANDU: 0.5 canisters/day PWR: 1.5 canisters/day
Disposal Canister Configuration	4 PWR assemblies (11,375 canisters with 4 assemblies each) 333 CANDU bundles (2,529 canisters with 333 bundles each)
Surface Facility and Operations	
Surface Waste Handling	1 Separate radioactive/non-radioactive material handling 2 Shared pool for CANDU bundles and PWR assemblies 3 Shared lag storage pool for PWR and CANDU canisters
Operational Worker Safety Radiation Protection	Disposal Canisters will be transported from surface to emplacement borehole in shielded cask.
Underground Facility and Operations	
Mining Method	Drill and blast
Host Rock Lithology	Fractured, saturated granite
Barrier Concept	Multiple Barriers
Underground layout	1. Provide redundant access to escape ways 2. Minimize footprint on surface 3. Minimize number of penetrations to the surface 4. Underground water drainage towards up-cast ventilation shafts 5. Minimum extraction ratio 30% 6. Separate radioactive/non-radioactive ventilation systems 7. Rock volume used as efficiently as possible 8. 200-m buffer around shaft to limit thermal effects 9. 40 m Drift Spacing 10. 500 m Repository Depth

Table 2. Base Case Design Components for Conceptual Design Evaluation

Design Parameter	Assumption
Borehole Configuration (based on temperature limit of 100o C at canister surface)	11. Vertical emplacement, separate areas (VSA)
	12. Bentonite buffer
	13. One canister/hole
	14. CANDU & PWR Borehole Depth: 8 m
	15. CANDU Borehole Spacing: 3 m
	16. PWR Borehole Spacing: 6 m
Emplacement scenario	17. Emplacement drifts backfilled and sealed upon waste emplacement
	18. Rooms sealed immediately after waste emplacement
Emplacement Concept	Waste must be retrievable
	Facility 20% expandable

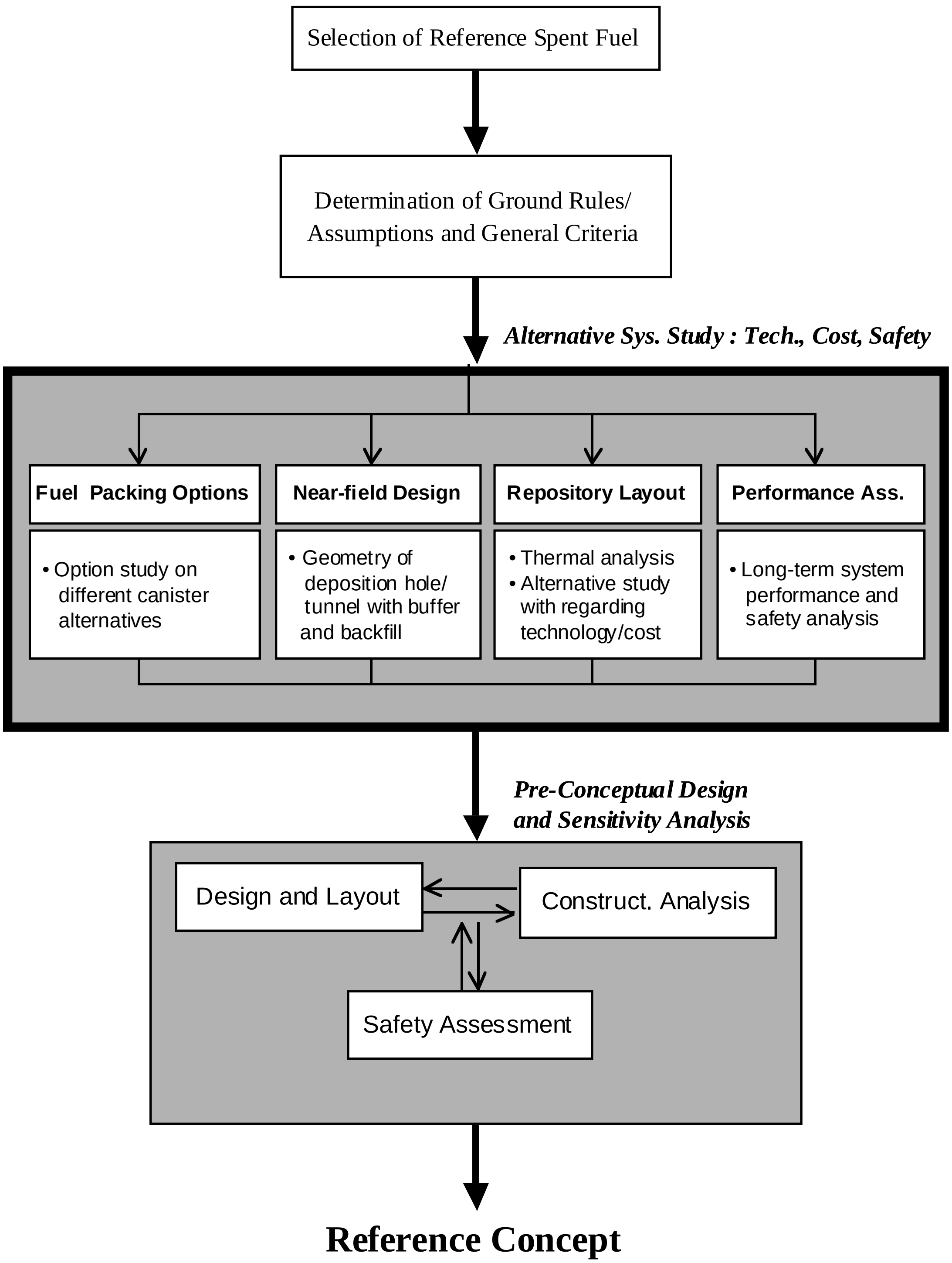


Fig. 1 Approaches for Developing of a Reference Disposal System